Hydroclimatology and biogeochemistry of the Amazon
1. Erosion

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ABSTRACT

The Amazon is the largest stream in the world. Its basin covers at least $7 \cdot 10^6$ km², which represents ~5% of the global continental area and almost 70% of the area of the continents localized in the equatorial zone, between 5°S and 5°N of latitude. The global tropical moist forest covers ~$9.35 \cdot 10^6$ km², so that the Brazilian evergreen rain forest represents at least 50% of this area. At Obidos, the most accessible downstream station for collecting data, the area concerned is $4.619 \cdot 10^6$ km².

The purpose of these two extended abstracts is to show how changes and oscillations of climate can significantly affect erosion as well as carbon and nitrogen cycles, and may also mask the degradations of the environment due to deforestation.

1. Hydroclimatology of the Amazon for the last 100 years

For the basin as a whole, climatic and hydrological parameters are given in Table 1. These coefficients are relatively high by comparison with other tropical regions. At Obidos ($4.619 \cdot 10^6$ km²), the average total runoff (1027 mm yr^{-1}, 4744 km^3 yr^{-1} or 149,700 m^3 s^{-1}) represents 11.9% of the global water discharge (40,000 km^3 yr^{-1}).

For the last 100 years, the average temperature has been decreasing slightly, between 28° and 26°C, while the rainfall and the stream flow have been rising together. Rainfall has been oscillating between 1600 (which, for Amazonia, is relatively dry) and 2800 mm yr^{-1} (which is relatively humid). The total runoff at Obidos exhibits very large interannual fluctuations, around the average of 150,000 m^3 s^{-1}, between 130,000 and 180,000 m^3 s^{-1} (Fig. 1).

For the purpose of modelization, the following linear relationships have been established which allows the evaluation of rainfall (P) and evaporation (E) if the total runoff (D_t) is known, or to evaluate runoff and evaporation if the pluviosity is given. These relationships are valid within the range of values measured during the last 100 years (Table 1):

$$P = -1120 + 3.153 D_t \quad (\text{mm yr}^{-1}) \tag{1a}$$

$$E = -1120 + 2.153 D_t \quad (\text{mm yr}^{-1}) \tag{1b}$$

$$D_t = +355 + 0.317 P \quad (\text{mm yr}^{-1}) \tag{2a}$$

$$E = -355 + 0.683 P \quad (\text{mm yr}^{-1}) \tag{2b}$$

Along the historical series both evapotranspiration and runoff increase together with

TABLE 1

Hydroclimatology of the Amazon basin as a whole: secular averages and extremes interannual characteristics between the most humid and the driest year

	Temperature (°C)	Humidity of the air (%)	Rainfall (mm yr^{-1})	Evapotranspiration (mm yr^{-1})	Runoff (mm yr^{-1})			K_e (%)	K_r (%)
					rapid	slow	total		
1969	26	90	2,646	1,452	414	780	1,194	45	35
Average	26.7	85	2,120	1,093	255	772	1,027	48	25
1919	28	80	1,470	649	58	763	821	56	18

K_e is the runoff coefficient ($=D_t/P$, where D_t=total runoff and P=precipitation); K_r is the surface runoff coefficient ($=D_r/D_t$, where D_r=rapid superficial runoff and D_t=total discharge).

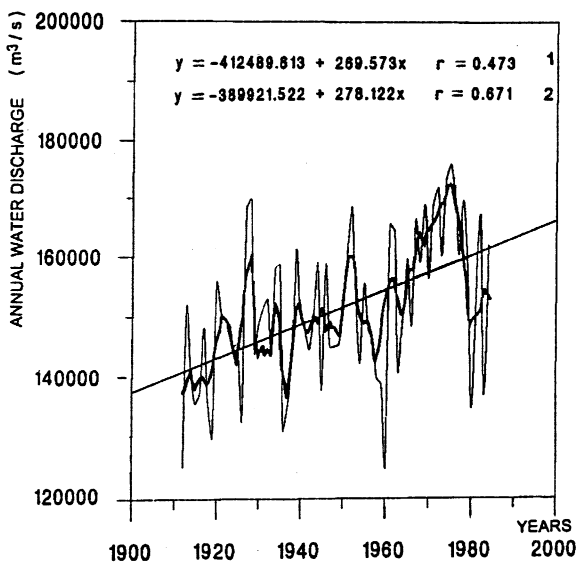

Fig. 1. Secular oscillations of the total water discharge (D_t, in m^3 s^{-1}) of the Amazon at Obidos. Annual discharge (*1*) and 3-year mobile averages (*2*) are presented. It shows that the water discharge oscillates, but rises from the first to the second part of the century.

rainfall. However, it should be noticed that K_e, the runoff coefficient ($K_e=D_t/P=355/P+0.317$), rises when P decreases or decreases when the pluviosity increases. However, if one considers different regions in the world, under a large variety of climates, one observes that K_e increases with rainfall. Further research will determine if the decrease of K_e when rainfall rises is a peculiarity of the Amazon basin or a characteristic of the climatic zone in which it is located.

2. Superficial runoff and mechanical erosion

It seems necessary to recall that the mechanical erosion occurs only in the rapid superficial runoff (D_r) and not in the slow and base infiltered runoff (D_b), while the chemical erosion plays a part in both superficial (D_r) and base water flows (D_b). The total water discharge (D_t), which flows out of the basin, is in fact the sum of the two contributions ($D_t=D_r+D_b$). It is not possible to solve the problems of erosion without solving first the questions of the superficial runoff in which it occurs exclusively.

For large basins, the superficial runoff is undeterminable directly but can be evaluated by models. The model which seemed the most appropriate acts with two water reservoirs (D_r and D_b), of a constant composition, but mixing in different proportions. Analysis of historical series would give simple answers, the accuracy of whose is increasing with the number of data collected and the duration of observations. The data used here, for the evaluation of the two components of the stream flow are those of the seven cruises of "CAMREX", organized between 1982 and 1984 (Jeff Richey, from the University of Washington, Seattle, U.S.A., leader of the project) and are given in Table 2.

Nitrate and sodium are exclusively concentrated in the infiltrating waters. Potassium comes from the two reservoirs but principally

TABLE 2

The runoff model: calculated concentrations of the chemical parameters, characterizing the two types of water flow in the Amazon basin

Runoff		(%)	NO_3	Na	K	POC_f	POC_c	POC_t	SS_f	SS_c	SS_t
Total	D_t	100	12.5	112.4	27	2.24	0.29	2.53	201	29	230
Superficial	D_r	29	0	0	57	5.96	0.82	6.78	582	93	675
Infiltrating	D_b	71	17.6	158.3	19	0.73	0.07	0.80	72	7	79

NO_3, Na and K are ions in solution (μmol l^{-1}); POC_f and POC_c are the particulate organic carbon (f=fine fraction; c=coarse fraction) (mg l^{-1}); SS_f, SS_c and SS_t are solid suspensions (f=fine, c=coarse, t=total) (mg l^{-1}).

from the surface runoff waters. Organic or mineral suspensions are all — as expected — mostly coming from the surface runoff waters. Other parameters, not listed, are variably distributed in the two types of reservoirs. In the water of the superficial runoff, the concentration of suspended solids is ~100 times greater for the mineral (SS_t=675 mg l^{-1}) than for the organic part (POC_t=6.78 mg l^{-1}). If one defines ME_m and ME_o as the mineral and the organic mechanical specific erosion, respectively (in t km^{-2} yr^{-1}), calculated by multiplying the concentration SS_t or POC_t by D_r, taking 1982 as an example, one obtains:

$$ME_m\ (t\ km^{-2}\ yr^{-1}) = 675 \times 366 : 1000 = 247\ t\ km^{-2}\ yr^{-1}$$

Data on superficial runoff and mechanical erosion for the Amazon basin at Obidos are presented in Table 3. Mechanical erosion of the Amazon is of the same order as the global erosion (152 t km^{-2} yr^{-1}). The concentration of suspended solids in the total water flow (D_t) decreases when the rainfall increases. However, in the superficial rapid runoff, the concentration is constant. In humid years, the mechanical erosion increases because the superficial runoff rises with rainfall. The model, based on the following linear relationships, is only valid for P values between 1500 and 3000 mm yr^{-1}:

$$D_r = 0.303P - 387 \quad (mm\ yr^{-1}) \quad (3)$$

$$D_b = 0.014P + 742 \quad (mm\ yr^{-1}) \quad (4)$$

$$ME_m = 0.205P - 261 \quad (t\ km^{-2}\ yr^{-1}) \quad (5)$$

and

$$ME_o = 0.00205P - 2.62 \quad (t\ km^{-2}\ yr^{-1}) \quad (6)$$

D_r progresses significantly with rainfall, while D_b progresses very slowly. This is simply because under humid climates groundwater reservoirs are close to saturation.

It can be shown that the specific mechanical erosion for both mineral and organic materials

TABLE 3

Superficial runoff (D_r) and mechanical erosion in Amazon, at Obidos, for the years 1982–1984

Year	P (mm yr^{-1})	D_t (mm yr^{-1})	K_e (%)	D_r (mm yr^{-1})	K_r (%)	ME_m (t km^{-2} yr^{-1})	ME_o (t km^{-2} yr^{-1})
1982	2,487	1,144	46	366	32	247	2.48
1983	1,834	937	51	169	18	114	1.14
1984	2,377	1,109	47	333	30	225	2.25
Mean	2,233	1,063	48	289	27	195	1.96

Specific erosion is given in t km^{-2} yr^{-1}. ME_m and ME_o are respectively the mineral (m) and the organic (o) mechanical erosion (ME).

TABLE 4

Evaluation of the average annual mechanical erosion in the Amazon for the last 100 years

Years	P (mm yr^{-1})	D_r (mm yr^{-1})	ME_m (t km^{-2} yr^{-1})	ME_o (t km^{-2} yr^{-1})
Less humid (1919)	1,470	58	39	1.05
First part of the century (1912–1932)	1,959	206	139	1.40
Average for the last 100 years	2,120	255	174	1.75
Last part of the century (1964–1984)	2,265	298	201	2.02
Most humid (1969)	2,646	414	279	2.80

ME is the mechanical erosion (m and o denote mineral and organic, respectively).

increases with rainfall in more humid times and decreases in less humid periods. Results of the estimated erosion for the past 100 years are in Table 4.

It can be shown also that the mechanical erosion should have been progressing with the humidity of the climate. If this secular tendency is attributed to deforestation, which in fact began in the 1970's, thus deforestation might also be responsible of an increase of humidity. This conclusion contradicts some ideas commonly expressed.

We believe that an increase of the mechanical erosion could be mostly the effect of climatic oscillations (natural?) which mask the possible effect of human deforestation. The precise knowledge of the rate of erosion will be therefore deferred as long as clearly established strategies will not exist for organizing historical series of observation, i.e. observatories in which data will be systematically collected over long periods of time.